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A Comparison of VLSTRACK (and Limited SCIPUFF) Predictions with Crystal Mist Experiment Results

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The accurate prediction of the location and magnitude of ground hazards resulting from bulk chemical releases is gaining importance in both operational and acquisition communities. The effectiveness of current and planned TMD systems will be evaluated in terms of protection to populations and assets from bulk chemical, and well as other, payload types.

One aspect of the prediction of ground hazards from bulk chemical releases is the correct modeling of agent transport from the point of release to initial ground impact. The transport and dispersion of released bulk chemical agents are quite sensitive to environmental factors. The level of sensitivity to environmental factors is a function of agent characteristics, such as droplet size and distribution, and release event, or source term, conditions. The Crystal Mist experiments, conducted in the mid 1990's by the US Army Space and Missile Defense Command, attempted to quantify agent cloud formation from known release conditions and transport through a measured atmosphere. The agent was simulated with glass beads of known size and distribution. Although data reduction was terminated before all results were fully analyzed, selected experiments can be expressed in the terms necessary for comparison with fast-running agent transport and dispersion models.

This paper presents a comparison of two Gaussian puff agent transport and dispersion simulations with the results of selected Crystal Mist experiments. The two Gaussian puff simulations chosen for this comparison are the Navy Surface Warfare Center (NSWC)-sponsored Vapor, Liquid, and Solid Tracking (VLSTRACK) computer model and the Defense Threat Reduction Agency (DTRA)-sponsored Second-order Closure Integrated Puff (SCIPUFF) model. Both tools are interfaced to the BMDO-sponsored Post-Engagement Ground Effects Model (PEGEM). The transport tools are exercised through the PEGEM interface. Measures of merit include the differences in cloud particle concentration and centroid position predictions with respect to the Crystal Mist experiment measurements. Issues that affect the accuracy of the simulation predictions are explored. These issues include release condition knowledge, simplifications inherent in Gaussian puff methodology, and the sensitivity to wind velocity measurements. Suggestions for improvement in future cloud transport experiments are presented.

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  - **Mr. Tim Cowles** *(USASMDC)* **- Technical Management**
  - **Mr. David Arasmith** *(KBM Enterprises)* **- Data Analysis**
  - **Mr. JL Harris** *(KBM Enterprises)* **- Technical Assistance**
  - **Mr. Mike Guthrie** *(Teledyne Solutions)* **- Technical Assistance**
  - **Mr. Tim Bauer** *(NSWC - Dahlgren)* **- Technical Assistance**

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The following individuals and their respective organizations have contributed greatly to the completion of this paper:

- Mr. Tim Cowles, USASMDC, provided technical management over this effort. His expertise with the Crystal Mist experimentation was critical to the analysis of the test data.
- Mr. David Arasmith, KBM Enterprises, initialized and performed the required PEGEM runs supporting this effort. Mr. Arasmith's efforts were also crucial to the data reduction and analysis.
- Mr. JL Harris, KBM Enterprises, provided excellent and timely reviews and critiques of both the comparison approach and the resulting paper.
- Mr. Mike Guthrie, Teledyne Solutions, provided technical assistance and located all of the Crystal Mist data referenced in this paper.
- Mr. Tim Bauer, NSWC, provided technical assistance with VLSTRACK.

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Topics

- Review of Crystal Mist Experimentation
- Limitations of Analysis
- Replication of 10 December 1993 Test
- Replication of 13 July 1994 Test
- Sensitivity of Predictions to Wind Velocity Measurements
- Issues and Recommendations
- References

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The following topics are reviewed in this paper:

- A brief explanation of the objective, approach and results of the Crystal Mist experimentation is provided. The test objectives, approach, description, and results are taken from the original test presentations and reports, and therefore reflect the goals of the personnel and agencies involved.
- Several of the issues and problems encountered in using VLSTRACK and SCIPUFF, both as interfaced to PEGEM and as stand-alone products, limited the ability to compare predictions to the Crystal Mist measurements. These limitations are discussed.
- The replication and subsequent comparisons to critical measurements for two Crystal Mist releases are provided.
- The sensitivity of the transport models to the quality of the wind velocity measurements is explored. The current comparative analysis revealed particular difficulties in achieving measured cloud movement with the measured wind velocity profiles. It is postulated that this sensitivity may present one of the more challenging aspects of further testing.
- Finally, several issues that surfaced during the conduct of this analysis are recapped. These issues lead to certain specific recommendations for future transport model development and test planning.

Crystal Mist Experimentation

Objective: Obtain Experimental Data to Evaluate and Validate Atmospheric Transport and Diffusion Models Applicable to Analysis of Bulk Chemical Threat TBM Intercepts by Lower Tier Systems

Approach: Perform Airborne Releases of 200 kg of Glass Beads with Diameters Ranging from 45 µm to 200 µm in a Well Measured Open Range Test Environment at Altitudes Ranging from 4.1 to 10.0 km MSL.

Experiment: 11 Successful Releases were Tracked with Visible, Infrared, Radar, and Lidar Airborne and Ground Sensors. Extensive Meteorological Data was Collected.

Results: Cloud Size, Centroid Track, and Particle Concentration were Selectively Reduced from Several of the Releases.

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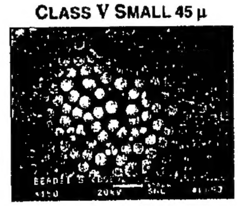

Scanning Electron Micrograph Image of Sample of Precision 45 µm Glass Beads. Precision Grade Beads were 90% True Spheres and 90% in the Size Range

The objective of the Crystal Mist experiments was to obtain data at lower tier TMD intercept altitudes that would permit the evaluation and eventual validation of atmospheric transport models.

The approach chosen for these experiments was to release 200 kg of glass beads of known and uniform size; then to track and characterize the resulting cloud for as long as possible after release, with a variety of assets. The glass beads, ranging from 45 µm to 200 µm in diameter, were released from a wing-mounted pod on a modified Learjet. This Learjet, termed the High Altitude Research Platform (HARP) and operated by Aeromet, was instrumented with sampling probes and an upward looking lidar. Release altitudes were varied from 4.1 to 10.0 km above mean sea level (MSL).

Eleven successful releases were conducted before the program was concluded. Unfortunately, only part of the data from the tests was analyzed. Worse, none of the data resulting from certain releases was ever reviewed. Data compilation, reduction, and fusing from multiple sensors proved more difficult, time consuming, and expensive that was originally estimated.

The results from the analyzed experiments included cloud size, centroid track, and particle concentrations, generally during the first hour after release.

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Limitations of Analysis

Data Availability:

- **The Scope of the Analysis is Limited by the Available Crystal Mist Data. The Final Report for the 1993 Tests and a Final Presentation Summarizing the 1994 Activities Include Sufficient Data to Support Comparisons to Only Two of the 11 Tests. The Limiting Factors were:**
  - Release Conditions
  - Meteorological Data

Cloud Track and Characteristic Output:

- **PEGEM is Designed and Implemented to Show the User the Hazardous Regions on the Ground after a Chemical, Biological, or HE Event. It Does Not Include Provisions to Visualize or Characterize the Clouds (in the cases of Chemical or Biological Agents) During Transport. VLSTRACK Provides the User with Limited Cloud Tracking and Characteristic Information During Transport. Even this Limited Information Can be Quite Voluminous to Manage, and Still May not Detail the Entire Mass of Agent, but only a Part.**
- **SCIPUFF (HPAC) Does not Appear to Offer the General User Any Cloud Track or Characteristics Data During Transport, either as Implemented in PEGEM or in the HPAC 3.2 Product.**

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Both Crystal Mist experiment data availability and the cloud track and characteristic output from the simulations limited the scope of the comparative analysis. As previously stated, much of the measurement data from the eleven Crystal Mist experiments was never reduced. Additionally, much of the data that was reduced was not captured in the available reports. It was only possible to reconstruct enough information to perform meaningful comparisons for two of the eleven tests. Although cloud track and characteristic data was available for additional test events, release condition and meteorological data was not.

All of the measurement data referenced in this paper was taken directly from the referenced Crystal Mist reports and presentations. The images included in this paper were scanned from those sources.

The cloud track and characteristic output available from the transport models in PEGEM also limited the scope and depth of the comparative analysis. PEGEM was designed and implemented to provide hazardous regions on the ground after a chemical, biological, or high explosive event. No provisions were included to visualize or otherwise characterize the chemical or biological agents during transport. The stand-alone VLSTRACK tool provides an abbreviated, albeit quite useful, cloud track output data. This data, although limited, can be quite voluminous. SCIPUFF does not appear to offer the general user any cloud track or characteristic data during transport, either as implemented in PEGEM or in the HPAC 3.2 product. Since the Crystal Mist experiment did not track the beads to the ground, no direct comparisons with SCIPUFF were possible.

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Replication of 10 December 1993 Test

Conditions:
- Release Point: 32.562 N, 106.372 W, 5492 m MSL
- Release Time: 13:48 MST (20:48 GMT)

Material Characteristics:
- MMD: 45 µm, $\sigma \approx 1.05$ (Assumed as 1.0 in Baseline Analysis)
- Mass: 200 kg
- Density: Assumed to be 2.7 g/cm^3

Meteorological Conditions:
- SMR, Oasis, Glover Rawinsonde Data at 21:00 GMT (but Correlation between Data Stream and Location Unknown)
- SMR Rawinsonde Data at 20:00 GMT and 21:00 GMT (but Correlation between Data Stream and Time Unknown)
- NOAA CO_2 Doppler Lidar (Glover) Wind Measurements at 20:33 GMT

Cloud Measurements:
- **Annotated Display of HARP Events and Ground Lidar Hits**
- Cloud Extents, Second High Altitude Research Platform (HARP) Intercept, 13 Minutes after Release
- Calculated Particle Concentration, Third HARP Intercept, 16 Minutes after Release
- **NOAA and Aerospace Ground Tracks - First 10 Minutes of Event**

Bold-Face Measurements Compared with VLSTRACK

Critical Missing Data:
- HARP Velocity and Flight Direction at Release
- Exact Time Duration of Release

Missing Source Term Data Affects Early Cloud Tracking and Concentration Predictions.

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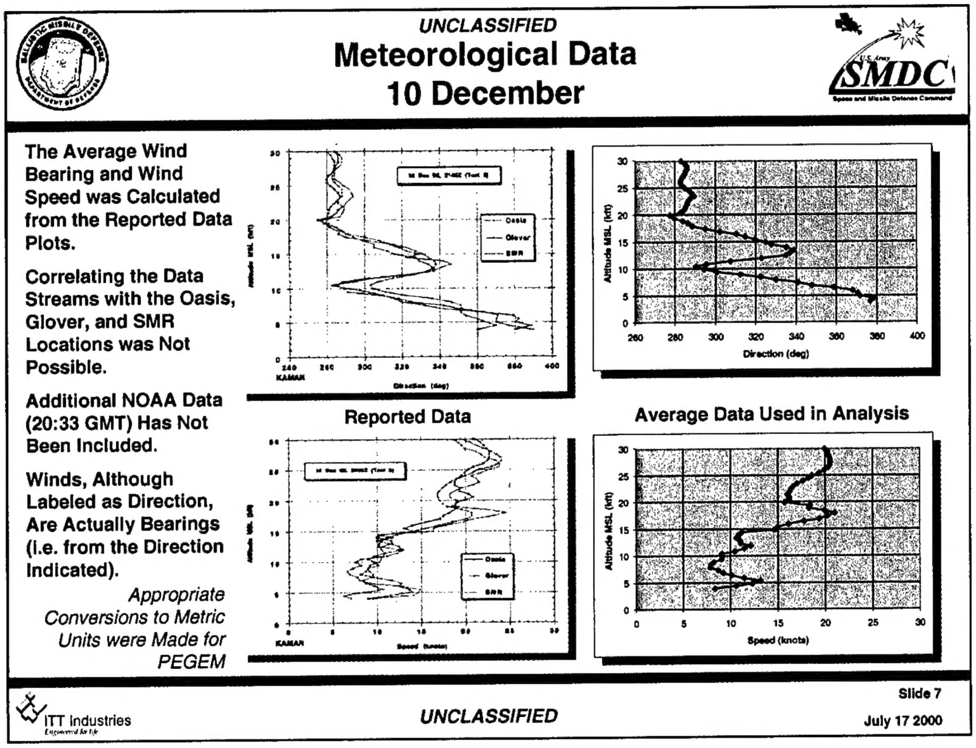
The 10 December 1993 Crystal Mist release was performed at the White Sands Missile Range (WSMR). Two hundred kilograms of 45 µm diameter glass beads were released from the HARP at an altitude of 5492 meters above MSL. The ground level at WSMR is approximately 1219 meters above MSL. Meteorological data was available at three separate times from four different locations. Limitations in the ability to correlate time and location with the individual met condition data streams forced the use of average conditions in this comparative analysis. This issue will be further detailed in the following slides.

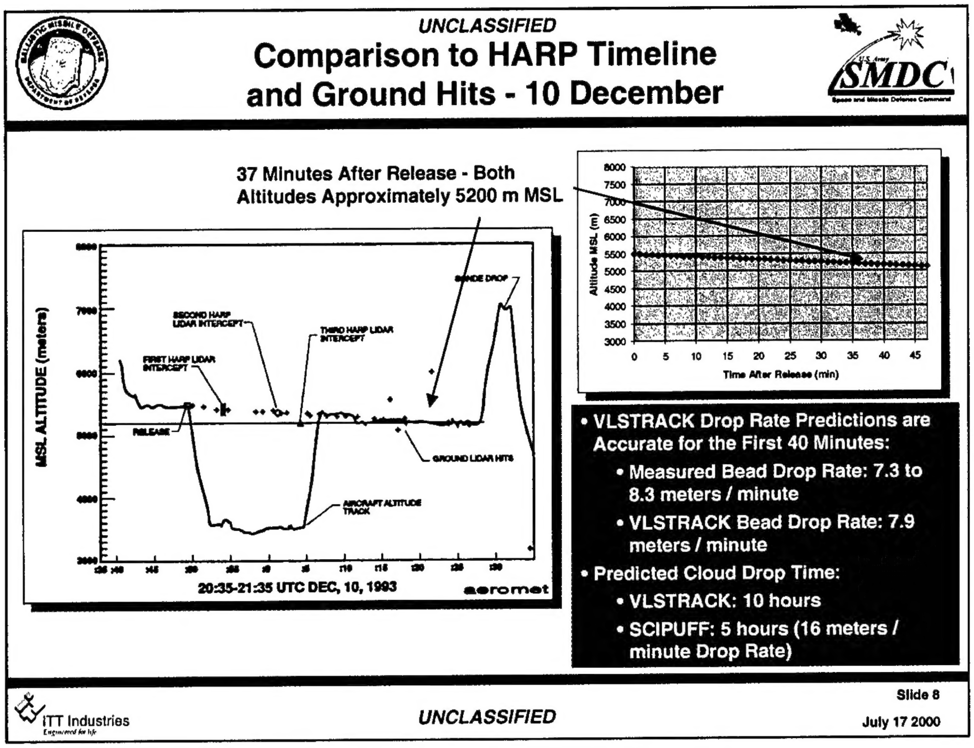
Available cloud tracking and characteristic data include an annotated display of HARP events and NOAA ground-based lidar hits. This annotated display incorporates cloud fall rate measurements. Cloud extents thirteen minutes after release are also available. A calculated particle (bead) concentration based upon measurements taken sixteen minutes after release is also available. Finally, ground tracks from the NOAA lidar and Aerospace visible and infrared-spectrum sensors are available for the first ten minutes after release. VLSTRACK comparisons to the fall rate and ground tracks are included in this paper.



The meteorological condition measurement data taken in support of the 10 December 1993 release is illustrated on the left hand side of the slide. The wind bearing and velocity data were measured from three separate locations on the hour before and after release. Unfortunately, color was used to correlate the individual meteorological data streams to the geographical locations on the original reported plots. That correlation has been lost in black and white reproductions of the report.

The average of data taken at Oasis, Glover, and the Small Missile Range (SMR) at 2100 Greenwich Mean Time (GMT) was used for the PEGEM analysis. Plots of the average data are shown at the right, for comparison. The meteorological data reference time is the time of balloon launch. Therefore, these balloons were launched approximately 12 minutes after the bead release. The balloons ascend at approximately 1000 feet per minute (5.1 meters / second), therefore the reading at the release altitude would have occurred at approximately 2114 GMT, or 26 minutes after the bead release.

The reported wind bearing data exceeds 360 degrees for altitudes below 7000 feet (2134 meters). The cloud tracking during the experiment terminated before the cloud reached that altitude. For modeling purposes, 360 was subtracted once the wind bearing exceeded that value.



The annotated HARP timeline illustrates the time and associated altitude of the centroid of the bead cloud and the aircraft. The cloud centroid descends to 5200 meters above MSL at approximately 35 to 40 minutes after release. The resulting descent rate is therefore between 8.3 meters / minute and 7.3 meters / minute. VLSTRACK predicts that the cloud centroid descends to 5200 m above MSL 37 minutes after release, which corresponds to a 7.9 meter / minute descent rate. Therefore, VLSTRACK predicts the centroid of the cloud will reach ground level approximately 10 hours after release.

An exact replication of the 10 December 1993 release was not possible with SCIPUFF, either as interfaced by PEGEM 3.5 or in the HPAC 3.2 product. However, comparable releases with 45 μm beads consistently produced bead fall rates of approximately 16 meters / minute. Extrapolating this fall rate to the 10 December Crystal Mist release yields a cloud fall time of approximately 5 hours.

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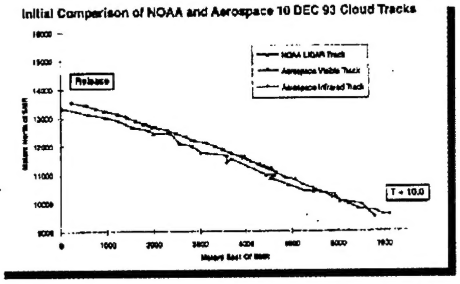
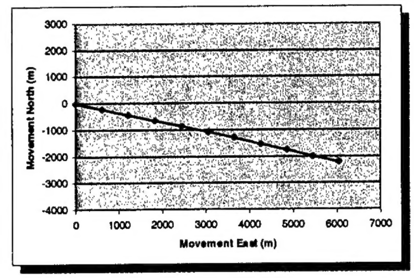
Comparison to Cloud Track 10 December





Cloud Centroid Movement During the First 10 Minutes after Release

- **VLSTRACK Underpredicts the Cloud Centroid Movement During the First 10 Minutes After Release:**
  - **Measured Cloud Centroid Movement: 7.8 km**
  - **VLSTRACK Cloud Centroid Movement: 6.4 km**
- **VLSTRACK Predictions are Consistent with the "Average" Wind Velocity Values Used in the Analysis:**
  - **A Constant 21 knot (39 km/hr) Wind** (Average Wind - 10 Dec) **Can Move Cloud 6.5 km in 10 minutes.**
  - **A Constant 25 knot (47 km/hr) Wind is Required to Move the Cloud 7.8 km in 10 minutes.**

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East/North Cloud centroid tracks from three separate ground sensors are available and documented for the first 10 minutes after release. These measurements, illustrated on the left side of the chart, show excellent agreement. Total cloud movement from the release point is approximately 7.8 km.

VLSTRACK underpredicts the cloud centroid movement, both in the easterly and southerly directions. The cloud centroid moves only 6.4 km in the VLSTRACK replication of the event. The VLSTRACK cloud movement prediction is consistent with the input meteorological conditions, however. A 7.8 km movement of the centroid of the cloud in 10 minutes requires a constant wind velocity of 46.8 km/hour, or 25 knots. The average wind velocity used in the comparative analysis at the release altitude was only 21 knots, or 39 km/hour. A constant wind of that magnitude will result in a cloud movement of approximately 6.5 km in ten minutes. One of the three meteorological data measurements did indicate the presence of a 25 knot wind at 18000 feet (5486 m) above MSL, but the relationship of the position of this reading to the release position is unknown.

Therefore, although inconsistent with the measured cloud track, VLSTRACK cloud movement predictions are consistent with the meteorological data used in the comparative analysis.

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Data Summary
13 July 1994

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Conditions:
- Release Point: 32.933 N, 106.050 W, 7300 m MSL (Assumed)
- Release Time: 18:00 MST (01:00 GMT) (Assumed)

Material Characteristics:
- MMD: 70 μm, $\sigma \approx 1.05$ (Assumed as 1.0 in Baseline Analysis)
- Mass: 200 kg
- Density: Assumed to be 2.7 g/cm^3

Meteorological Conditions:
- Desert Rock, Yucca Flats, Rawinsonde Data, Before and After Release Averages
- Average of All Times Used in PEGEM Trials

Cloud Measurements:
- **Cloud Tracks from NOAA Lidar, 60 Minutes after Release**
- Cloud Extents, NOAA Lidar, 48 Minutes after Release
- Calculated Particle Concentration, Aeromet Lidar, 47 Minutes after Release
- **Measured Vertical Bead Distribution, NOAA Lidar, 29 to 54 Minutes after Release**

Bold-Face Measurements Compared with VLSTRACK

Critical Missing Data:
- Exact Time of Release
- Exact Point of Release
- Exact Time Duration of Release
- HARP Velocity and Flight Direction at Release

As with the 10 December Test, Missing HARP Flight Direction and Velocity Impacts Early Cloud Tracking and Concentration. Time and Point of Release are Not a Critical Since Cloud was Not Tracked to the Ground.

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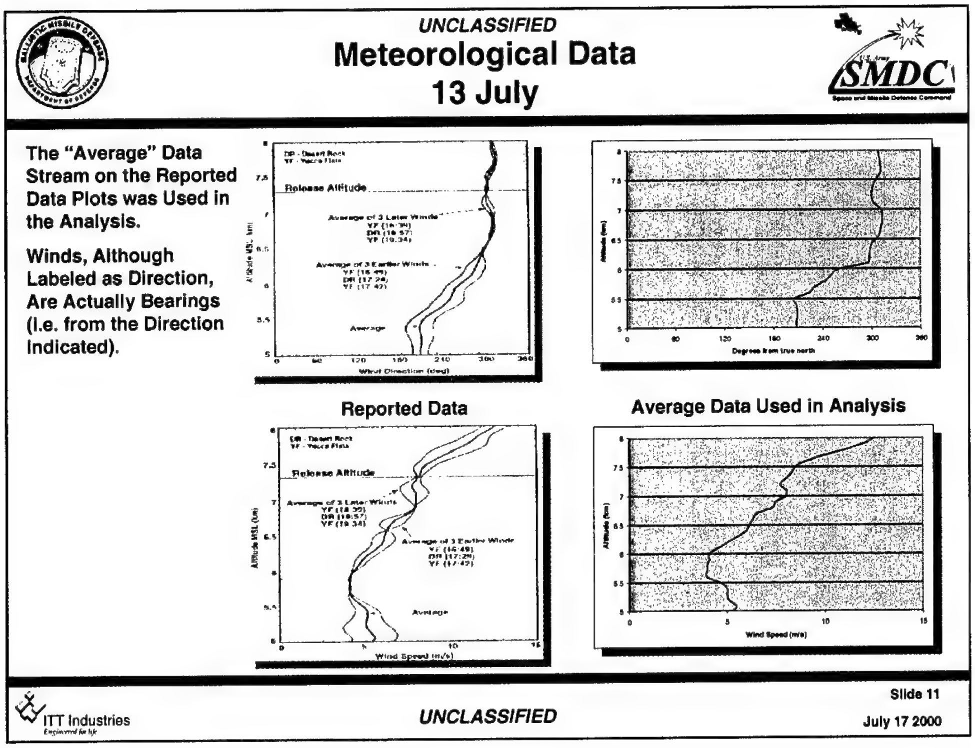
The 13 July 1994 Crystal Mist release was performed at the Nevada Test Site. This drop examined the characteristics of a cloud populated with 70 μm diameter beads. The exact time and altitude of the release are unknown, but have been approximated from the documented cloud characteristics measurements.

Meteorological data is available from two sites both before and after the bead release. Again, the data cannot be correlated to a balloon launch location, forcing the use of a set of average meteorological conditions.

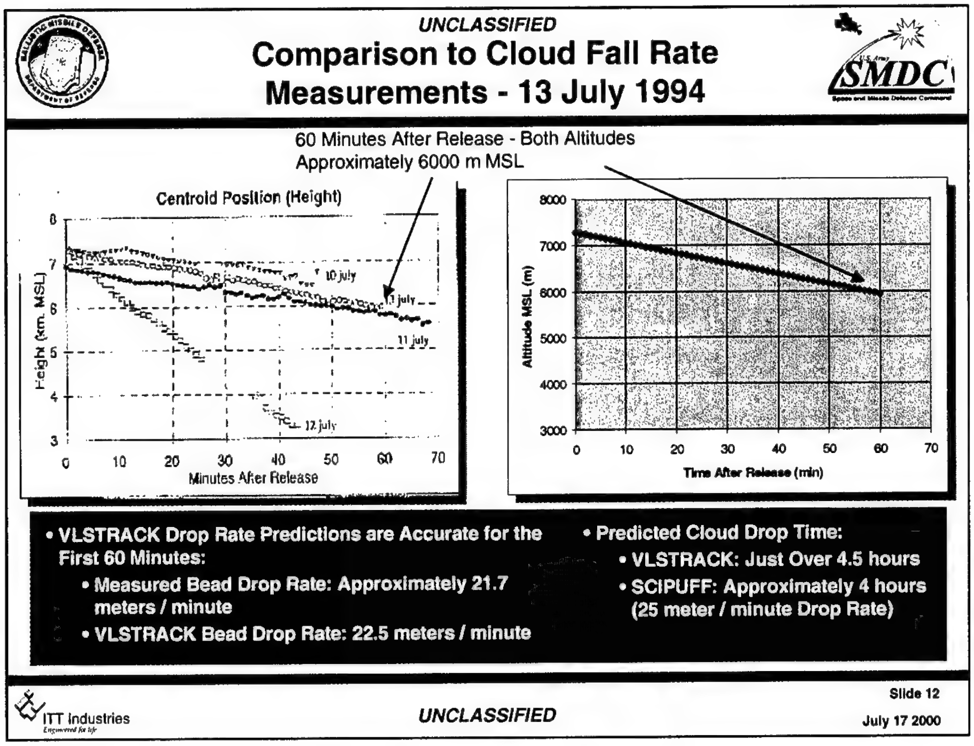
Cloud centroid altitude and East/North tracks are available for the first 60 minutes after release. VLSTRACK is compared to the cloud track data from the NOAA lidar for convenience. The NOAA lidar measurements were compared to the measurements from other assets during initial reduction of the Crystal Mist data. This comparison was favorable. The NOAA lidar data was further reduced to provide vertical bead distributions at selected times during the first hour after release. VLSTRACK particle concentration predictions have been compared to these measurements.

As with the 10 December event, certain critical release-specific characteristics are missing from the available documentation. None of these omissions affect the ability to compare gross VLSTRACK cloud movement predictions to the Crystal Mist measurements. However, time specific cloud volume, concentration, and shape comparisons are compromised by the missing data items.



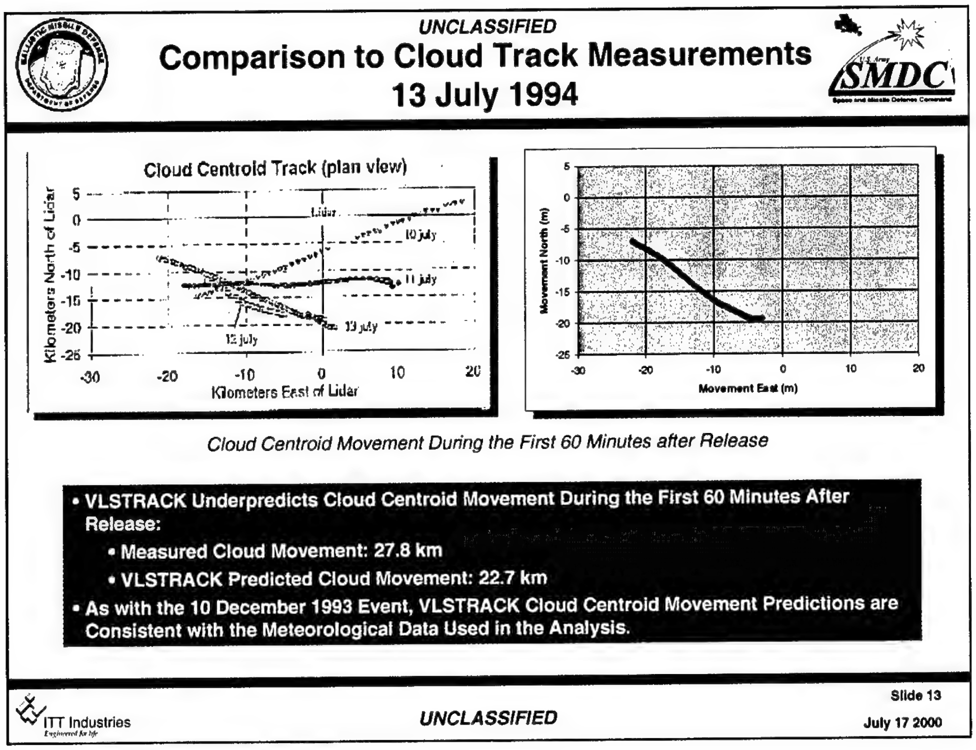
The reported meteorological data and subsequent "average" data used in the PEGEM comparison analysis is presented in the four graphs. The Crystal Mist experiment summary for the 13 July release averages three meteorological samplings before and after the release into two data streams. Single "averages"of wind bearing and velocity are then calculated. The single averages of wind bearing and velocity were used in the PEGEM analysis.

Very little variation in wind bearing is noted from the release altitude (7.3 km) to about 6.4 km above MSL. Up to a 2 meter / second (7.2 km / hour) variation is noted in wind speed for this altitude regime between the average of three earlier winds and the average of three later winds. The average of three later winds is lower.



The fall of the 70 μm bead cloud centroid, as measured during the first hour after release by the NOAA lidar, is compared to the VLSTRACK prediction. The chart on the left illustrates the cloud centroid height with respect to time after release for four of the Crystal Mist events (10, 11, 12, and 13 July 1994). The NOAA lidar measured approximately a 21.7 meter / minute (36 cm/sec) cloud fall rate. VLSTRACK predicts a 22.5 meter / minute (37.5 cm/sec) cloud fall rate.

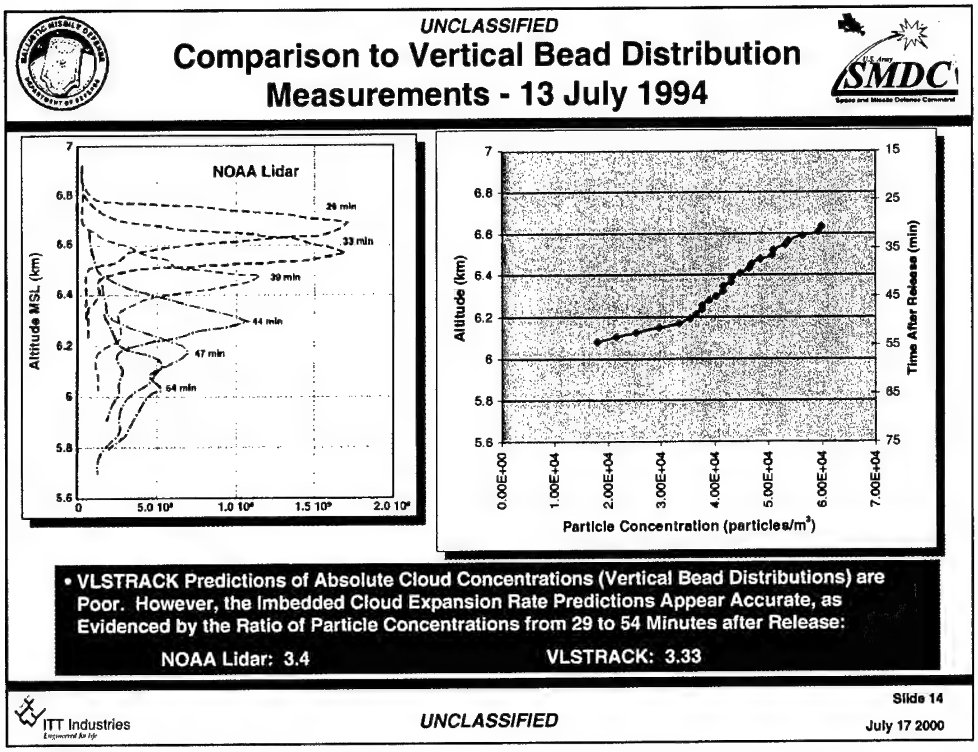
Given this fall rate and a consistent estimate of the ground height above MSL, VLSTRACK predicts the cloud centroid will reach the ground approximately 4.5 hours after release. The SCIPUFF prediction of a 25 meter / minute bead drop rate results in a 4 hour cloud fall time.



The cloud East / North centroid track for 13 July release (as well as the 10, 11, and 12 July releases) as measured by the NOAA lidar is presented on the chart to the left. As expected for a wind bearing of approximately 300 degrees (winds from the northwest) the cloud moved toward the southeast on the. VLSTRACK correctly captures the cloud movement direction, but as with the 10 December 1993 test, underpredicts the total distance of cloud movement.

The NOAA lidar measured a 27.8 km movement of the cloud centroid during the first 60 minutes after release. VLSTRACK predicts only a 22.7 km movement of the cloud centroid. Achieving the 27.8 km cloud movement would require a constant wind velocity of 7.7 meters / second in a constant direction. The average wind velocity used in the VLSTRACK analysis is approximately 7.5 meters / second from the release altitude to 6800 meters above MSL. The direction is also fairly constant for that altitude range. VLSTRACK predicts the centroid of the cloud descends to that altitude approximately 22 minutes after release. Assuming a constant wind velocity of 7.7 meters / second, the cloud would move 10.2 km. VLSTRACK predicts, using the average meteorological conditions for 13 July, a movement of 10.2 km.

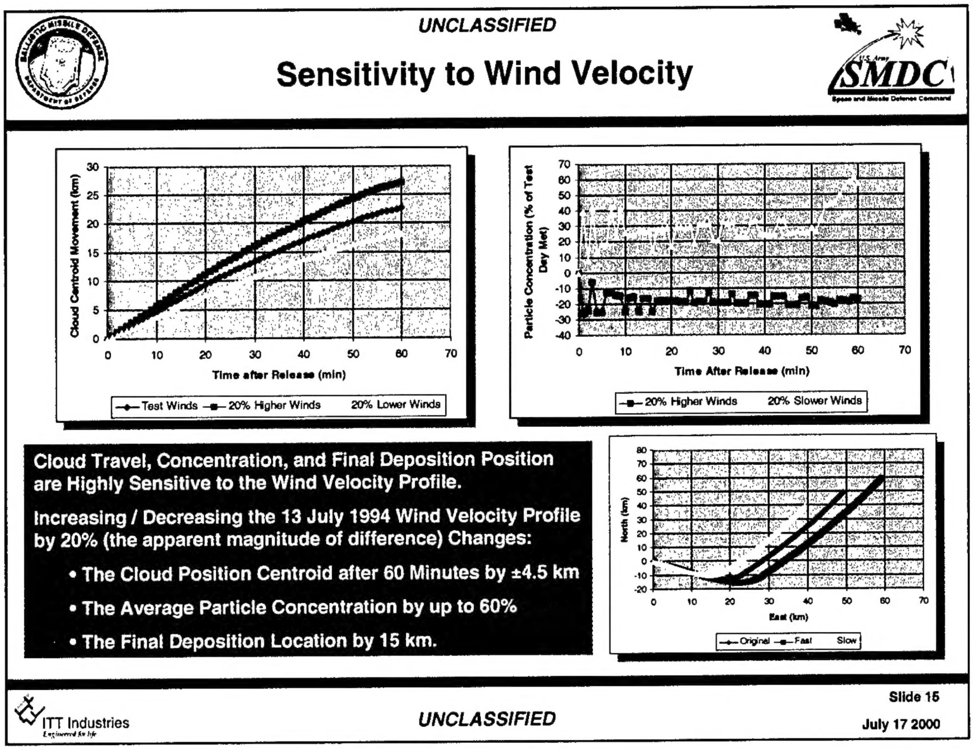
Based upon the analysis, it appears that VLSTRACK predicts cloud movement consistent with the input meteorological conditions. It is probable that the average meteorological data used in the analysis does not adequately replicate the conditions seen by the cloud.



Any cloud dimension, volume, and particle concentration analysis will be highly sensitive to the release conditions, especially for relatively short periods of time after release. Many of the bead release characteristics necessary for good early time cloud volume and concentration modeling are not included in the available Crystal Mist experiment references. However, the cloud expansion rate should be relatively insensitive to the release conditions, given that general assumptions of velocity, release time, and release geometry are adequate.

Selected NOAA lidar cloud measurements were analyzed to assess the vertical bead concentration with respect to time during the first hour after release. These measurements are illustrated on the left side of the chart. As can be seen, the cloud is elongating vertically between the 29 minute slice and the 54 minute slice. The peak bead concentration is also reduced by a factor of 3.4 during the 25 minute time span.

The VLSTRACK predictions of average particle concentration do not compare well to the NOAA lidar measurements. However, both the reduction of the average bead concentration and the altitude of the cloud centroid match the measurement data quite well. The ratio of average particle concentration at 29 minutes after release to 54 minutes after release predicted by VLSTRACK is 3.33.



The prediction of cloud track position, cloud characteristics, and final deposition location are quite sensitive to the velocity profile. The analysis of the 13 July 1994 Crystal Mist release suggests that a difference of up to 20% may have existed in the reported "average" wind velocity profile and the profile seen by the cloud. Further analysis of the sensitivity of total cloud movement, average particle density, and final deposition location was performed to bound the differences that could be expected between measured and predicted cloud characteristics.

A ±20% constant variation in the wind velocity for the 13 July 1994 release induces a 9 km change in the cloud centroid position one hour of travel. Assuming the average winds reported at the test site were accurate, the cloud centroid would move approximately 22.7 km 60 minutes after release. If the winds were uniformly 20% higher, the cloud centroid would move 27.2 km. The NOAA lidar measured a 27.8 km movement during the first 60 minutes. Reducing the wind profile by 20% moves the cloud only 18.2 km.

The average particle concentration prediction, a direct indicator of cloud expansion rate, is very sensitive to decreases in wind velocity. At the end of the 60 minute time period, VLSTRACK predicts a 60% higher average concentration for the cloud in the lower velocity wind-field as compared to the winds reported at the test site. Increasing the winds by 20% only reduced the average concentration by approximately 16%. The noise in the data is caused by granularity in puff overlapping made during the analysis process, not directly by VLSTRACK.

Finally, although not part of the Crystal Mist experiment, it was interesting to note the difference in the final deposition of the cloud centroid. Changing the wind profile by 20% displaced the centroid deposition location by almost 15 km.

Issues and Recommendations

- **The Gaussian Puff Transport Tools Used by PEGEM, and Therefore PEGEM itself, Are Designed to Present the Ground Hazard to the User, Not Incremental Steps in the Transport Process. This Basic Limitation Complicates Model Comparison with Any Transport Test Data:**
  - VLSTRACK Provides the User with Part of the Cloud Description During Transport via an Optional Output File - Aiding Comparisons by the User.
  - SCIPUFF Does not Provide Any Transport Data to the User.
- **VLSTRACK Early Time (within the First Hour After Release) Fall Rate Predictions Track Closely With the 45 μm and 70 μm Bead Releases.**
- **VLSTRACK Underpredicts Cloud Centroid Movement During Both Events, But Does Correctly Capture the Direction.**
  - Analysis of the Wind Velocity Data Measured on the Test Days Supports the VLSTRACK Cloud Track Predictions, not the Measured Tracks.
  - One Region of Limited Wind Variability on the 13 July Release Shows Very Close Correlation Between the Measured Cloud Movement and VLSTRACK.
  - Sensitivity Analyses Indicate only a 20% Variation in the Wind Profile Can Account for the Predicted Location Errors.

PEGEM, along with VLSTRACK and SCIPUFF, are designed and implemented to present the location and extents of any collateral effects on the ground. This limitation negatively impacts the ability to compare simulation predictions to measurement data from experiments such as Crystal Mist. Fortunately, VLSTRACK does provide the user with a subset of the total cloud characteristics during transport. This output was adequate to evaluate cloud centroid drop rate, position, and total cloud expansion rate, with selected Crystal Mist measurements.

VLSTRACK predictions of cloud drop rate compare favorably with the two analyzed Crystal Mist experiments. Differences between the predicted and measured drop rates were measured fractions of a meter / minute. Integrated over a long period of time, those differences certainly can become large, but given the small bead sizes of the released samples may still only have limited "real" impact. Transport times will still be measured in hours, rather than minutes.

VLSTRACK underpredicted the total cloud movement during both analyzed releases, however the VLSTRACK predictions were consistent with the input meteorological data. Further, close analysis of the wind velocity measurements does not support the measured ground tracks, unless up to a 20% differential in measured versus actual wind velocity is applied. This sensitivity to wind velocity emphasizes the need for accurate measurements at any future tests and should influence any tactical use of this type of tool.

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Issues and Recommendations

- **VLSTRACK, and Most Likely all Gaussian Puff Models, Does Not Appear to Accurately Predict the Particle Concentrations and Absolute Cloud Shapes Measured During Crystal Mist. The Cloud Expansion Rate Measured During the First 59 Minutes of the 13 July 1994 Test Was Correctly Modeled by VLSTRACK, However - Lending Credence to the Accuracy of the Transport Model.**
- **Although Interesting, the Bead Sizes Chosen for Analysis During Crystal Mist May Not Reflect the Size and Mass of the Spectrum of Drops of Interest. Future Test Series May Want to Consider:**
  - Releasing Larger Beads (drops) From Lower Altitudes and Attempting to Track the Cloud as it Nears the Ground.
  - Releasing Larger Beads (drops) at 10 to 30 km Altitudes both Statically (such as a Balloon Drop) and Dynamically (such as a Release from a Sounding Rocket). The Static Tests Will Validate Drop Rate and Diffusion Models, While the Dynamic Tests Will Serve to Verify the Early Cloud Deceleration Modeling.

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Gaussian puff models may never provide truly accurate predictions of cloud shape, extents, and volume at a given point in time after release due to the simplifications inherent in the puff type modeling. However, the critical cloud expansion rate prediction seems to be correctly captured by VLSTRACK. Exact cloud shape may be of limited importance, as long as differences in the transport response of different sized drops is correctly captured.

Finally, the bead sizes chosen for release during Crystal Mist may not reflect the size and mass spectrum of drops of interest. Future test programs may want to consider:

- Releasing larger beads or drops from lower altitudes and attempting to track the cloud as it nears the ground. Higher altitude release of large beads will also be interesting.
- Performing both static, such as balloon drop, and dynamic releases. The static releases will validate drop rate and diffusion models, while the dynamic tests will serve to verify early cloud deceleration modeling. In both cases, it will be important to quantify the release characteristics. This will be most challenging during dynamic releases.

This analysis has attempted to use the Crystal Mist data for the stated purpose of the experimentation. Many of the measurements captured during the experiments could be directly correlated with VLSTRACK predictions. As such, for the two releases analyzed, the Crystal Mist experiments should be considered a success. Further, excellent correlation between VLSTRACK predicted and measured fall rate and cloud expansion rate was noted. The sensitivity of cloud centroid motion to wind velocity, especially for these small beads, must be remembered when planning future tests and when using PEGEM to predict the location of a collateral hazard.

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The listed references were used in the performance of the Crystal Mist / PEGEM comparative analysis and the preparation of this paper.